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Abstract. Broadband receiver functions derived from teleseismic P-waveforms recorded on Regional Seismic Test Network (RSTN) stations in Eastern North America contain detailed information about the crust-mantle boundary. This paper examines receiver functions from three stations (RSCP, RSNY, and RSON) to illustrate the variability in response of the continental "Moho" and to demonstrate the utility of broadband data in studying these variations. Of particular interest is the clear evidence for frequency-dependence of the amplitudes of converted phases arriving from the crust-mantle boundary. The shear velocity structures for these stations obtained by inverting the radial component of the receiver functions in the time domain indicate that this frequency-dependence is a measure of the "sharpness" of the crust-mantle boundary region.

Introduction

Probing the structure of the continental crust-mantle boundary (CMB) has traditionally involved the seismic refraction technique. Although the CMB has often been pictured as a first-order velocity discontinuity, the "Moho", recent investigations find this model to be the exception rather than the rule (e.g. Prodehl, 1977; Prodehl et al., 1984; Deichmann and Ansorge, 1983). Although there is no precise seismological definition of the CMB, we are using the transition from shear velocities of about 3.7 km/s to about 4.6 km/s as a working definition. The prevailing view of this important boundary is that of a transition zone varying in thickness from only one or two to more than 15 km in some regions. These results from refraction data are consistent with models obtained from deep crustal reflection profiles which account for the discontinuous nature of Moho reflections with laminated transition zones (e.g. Hale and Thompson, 1982; Oliver et al., 1983). The purpose of this paper is to examine the response of the continental CMB on a different type of seismic data, teleseismic receiver functions. We compare models of the CMB derived from our data with those of other studies to demonstrate some interesting similarities as well as the variability of CMB responses observed in teleseismic receiver functions. We also follow the lead of Hale and Thompson (1982) and present a synthetic receiver function for the Ivrea-Verbano zone to illustrate one possible response for a geologically realistic CMB model. We conclude from this comparison that the analysis of teleseismic receiver functions is a potentially useful method of delineating the structure of the continental CMB that provides complimentary information to that obtained through other seismic methods.

Broadband Receiver Function Analysis

Teleseismic body waveforms have often been used to infer crustal structure beneath isolated seismic stations (see for a review, Owens et al., 1984). Recently, we refined and extended these techniques to take advantage of the new digital broadband seismograph stations in order to examine the detailed crustal and upper mantle structure beneath these sites (Owens, 1984a,b; Owens et al., 1984). To utilize teleseismic P-waveforms, we must isolate the response of the crust and upper mantle velocity structure, the receiver function, from source and path effects which also influence the recorded seismogram. Because we are primarily interested in converted waves of the P-to-S type, the horizontal components of the receiver function are isolated using a deconvolution procedure suggested by Langston (1979) and examined in detail by Owens (1984a). In this process, source effects are removed by deconvolving the vertical component from rotated radial and tangential components. The results are then convolved with a simple gaussian time function to produce smooth estimates of the horizontal receiver functions. At this point, receiver function estimates from events clustered in both distance and back azimuth from a station are stacked to provide a single good quality estimate for each of the horizontal components.

The detailed receiver functions obtained from broadband data are modeled using a time-domain inversion routine. We assume a horizontally layered model and invert the radial receiver function for the vertical shear velocity structure at each back azimuth. The variation in the results with azimuth are indicative of gross lateral variations in structure around the station. This method has provided strong evidence for tectonically significant velocity variations around two RSTN stations (Owens, 1984b; Owens et al., 1984).

In this study, we use the broadband receiver functions to examine arrivals from the CMB recorded on the midperiod passband of RSTN stations RSCP, RSNY, and RSON (Figure 1). The midperiod passband is flat to velocity from 0.018 to about 1.2 Hz. By varying the frequency content of the gaussian time pulse in our source deconvolution, we can examine the receiver functions for all or part of this broad passband. Figures 2a-c show radial receiver functions for the three stations. The longer period receiver functions are low pass filtered (frequency less than 0.35 Hz) versions of the broadband functions. The examples shown in Figure 2a-c were chosen because our inversion technique gave excellent fits to these data and because they are clear simple cases of the frequency-dependent effects we seek to examine. Data from other back azimuths at these sites are of varying quality, but the derived results are consistent with the examples discussed here.

The shear velocity models determined by inverting the broadband radial receiver functions are shown in Figures 3a-c. Only the portions of the models between 30 and 60 km depth are shown to highlight the labeled CMB region. Discussions of the entire crustal model for each are published elsewhere (Owens et al., 1984; Owens, 1985). Arrival times for primary (Ps) and multiple converted phases for the depth ranges shown in Figure 3 are indicated on Figure 2. This clearly shows that increases in long-period amplitudes relative to broadband amplitudes in the receiver functions, when they exist, are associated with converted phases from the CMB under these sites.

This relationship is best illustrated at RSNY (Figure 3c) where both the long-period Ps phase and crustal reverberations have larger amplitudes than the corresponding broadband arrivals. Except for slight complications due to midcrustal structure, the long-period receiver function at RSNY looks like a simple layer over a half-space response (see, for example, Langston, 1979). This long-period response could be modeled by a 46 km thick crust with an average shear velocity of 3.8 km/s. Inverting the broadband receiver function produces a different picture of the CMB. The lack of large amplitude converted phases in the broadband response required a smoother CMB region. The transition from crustal velocities to upper mantle velocities occurs over a depth of 10 km beginning at just over 41 km.

In an earlier study, Owens et al. (1983) showed that linear velocity transitions produce similar frequency-dependent converted phase amplitudes while a first-order velocity discontinuity produces frequency-independent arrivals. This behavior has a simple physical explanation. The wavelengths of the long-period waves are greater than the thickness of the transition zone and therefore are affected only by the net velocity contrast across the zone, i.e. the transition zone appears to be a first-order boundary at sufficiently low frequencies. However, higher frequencies are sensitive to the details of the transition zone due to their shorter wavelengths, so the zone can have an influence on the amplitudes of converted phases on the broadband receiver functions.

This relationship between relative amplitudes of long-period and broadband converted phases and the nature of the CMB appears to be supported at our other stations, but not without complications. At RSON, where the CMB appears to be about 2-4 km thick with nearly a first-order discontinuity at 42 km depth, the Ps conversion is not frequency-dependent. However, despite the "sharpness" of the CMB beneath RSON, the CMB multiples are not discrete pulses and the long-period to broadband comparison does not unambiguously show the expected frequency independence. LAN, a broadband station located in the Mohave Block of southern California, does contain discrete multiples for a sharp CMB of about 2 km thickness and 0.8 km/s shear velocity contrast (Wilhelm, 1984). Their absence at RSON may be due to interference with arrivals from depths of 30 to 38 km, or to lateral variations in the CMB which effectively destroy the multiples.

The CMB is also a thick transition zone beneath RSCP (Figure 3a). The zone extends from 38-51 km depth, but the velocity increase occurs in two distinct steps (labeled T1 and T2 on Figure 3a). This shear velocity structure correlates closely with a P-velocity profile derived from refraction data (Prodehl et al., 1984; Zandt et al., submitted to Tectonophysics). Owens et al. (1984) obtained error bars for their velocity determinations of between $\pm$.10 and .16 km/s which means the smaller scale structure of this zone is not well resolved. This broad transition zone gives rise to a frequency-dependent Ps arrival at RSCP (Figure 3a) very similar to that at RSNY, although the amplitudes of the crustal reverberations are not enhanced at longer periods.

Discussion

In the previous section, we presented observational evidence of the relationship between frequency-dependent converted phase amplitudes in teleseismic receiver functions and the nature of the CMB beneath the recording site. The emergence of prominent long-period phases at stations where inversion of the broadband receiver functions indicates the existence of a thick crust-mantle transition zone agrees with our physical intuition concerning the effects of velocity transitions. However, only the RSNY receiver function behaves as expected for both primary and reflected converted phases if this phenomena was solely responsible for the observed effects. As a starting point for examining other effects and to provide some direct geologic input into the nature of the continental CMB, we computed a synthetic receiver function for the Ivrea-Verbano zone using the model presented by Hale and Thompson (1982) based on the velocities measured by Fountain (1976). The Ivrea-Verbano zone, Italy is thought to be a section of the lower crust and upper mantle exposed by the Alpine Orogeny (Fountain, 1976). Discussions of the petrology of this zone can be found in these references. The model consists of a homogeneous crust overlying the Ivrea zone (Figure 3d). Shear velocities were calculated assuming Hale and Thompson's (1982) P-velocities and a Poisson solid. The crustal thickness was fixed so arrival times for converted phases from the Ivrea zone would agree with observed arrival times in Figures 2a-c.

The resulting Thomson-Haskell synthetic receiver function is remarkably similar to the observed data in many respects (Figure 2d). The Ivrea synthetic has Ps and multiple converted phases that show frequency-dependent behavior similar to that at RSNY and, to a lesser extent, RSCP. A model which smooths the Ivrea Zone to include only two layers between 41 and 46 km depth will produce a synthetic response that does not differ from Figure 2d at a level we believe would be significant in noise-contaminated data. We conclude that broadband teleseismic waveforms are only sensitive to average trends in the CMB velocity profile and are not biased by velocity laminations thinner than about a kilometer. This highlights the interesting complementary nature of this method and near-vertical reflection profiling which can demonstrate the existence of thin laminations, but cannot recover average velocity information in the deep crust.

The petrology of the Ivrea Zone suggests that in this case, the CMB consists essentially of high-velocity lower crustal (mafic) rocks separated from mantle (ultramafic) rocks by a sharp (<1 km) boundary. Similarly, at RSCP and RSNY, our derived CMB models consist of layers of shear velocity 4.0-4.3 km/s overlying layers with velocities greater than about 4.5 km/s. If we identify mantle rocks with velocities above about 4.5 km/s, then the crust-mantle transition is as sharp (<3 km) at RSCP and RSNY as it appears in our RSON results. This sharper crust-mantle boundary is labeled "M" on Figures 3a-d. From this observation, we suggest that the frequency effects observed in Ps and multiple converted phases appear to be indicative of the presence of high-velocity lower crustal material forming a CMB zone. There is good evidence of similar lower crustal structures in seismic refraction data (Deichmann and Ansorge, 1983) although we are not aware of any work incorporating such information into models of crustal evolution.

Despite our enlightening results in probing the CMB, the single station teleseismic waveform method is hampered by some fundamental drawbacks, such as the assumption of lateral homogeneity. Overcoming the limitations in our knowledge of the effects of realistic earth structures on teleseismic receiver functions requires additional effort on several fronts. The foremost need is implementation of techniques capable of modeling the impact of laterally-varying structure on teleseismic receiver functions.

Most seismic reflection evidence indicates that the fine scale structure of the CMB can vary considerably over short lateral distances (Hale and Thompson, 1982; Oliver et al., 1983). Our receiver functions sample the CMB over lateral distances approximately equal to the CMB depth. In our present examples, this is about 40 km. Since the CMB structure almost certainly varies over this distance, we must be able to quantify the possible effects of this variation on our broadband waveforms. If these lateral variations are being mapped into our vertical velocity structure, it is important that we document the extent of this bias through model studies.

The ability of receiver function analysis to delineate vertical velocity structure with very little lateral averaging is a unique advantage it has over other seismic methods of probing the continental lithosphere. We have shown that this method is sensitive to the structure of the CMB. The broad bandwidth of the RSTN data presents the opportunity to examine the frequency-dependent effects of the CMB on teleseismic receiver functions. We have shown that the method is useful in modeling this structure and may fill an important niche among seismic techniques available to study the continental CMB. Some deficiencies in the single station teleseismic waveform modeling method could be alleviated by the use of arrays of broadband instruments. In the future, application of this method to such arrays deployed through the PASSCAL-IRIS initiative may make possible much more detailed shear wave velocity maps of the continental lithosphere.

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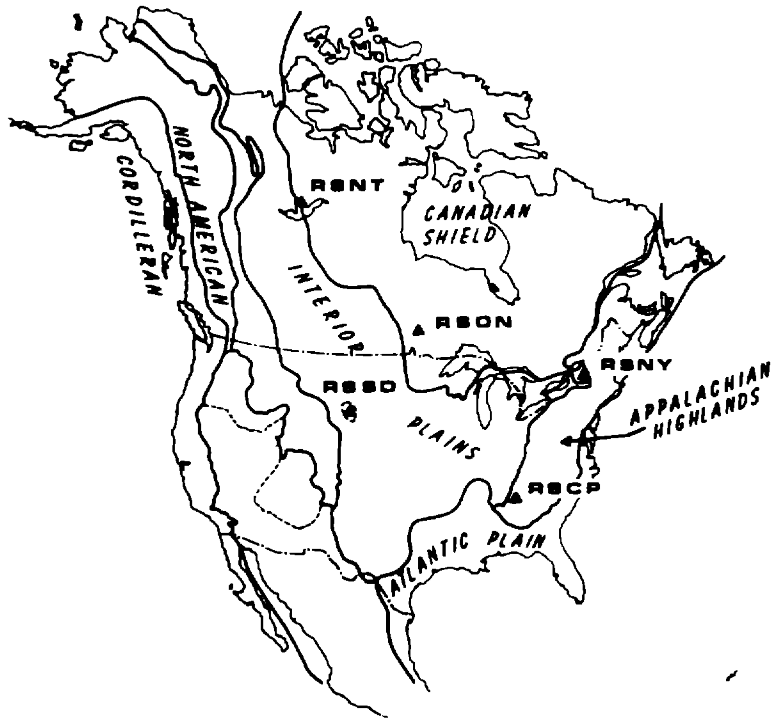
FIGURE CAPTIONS

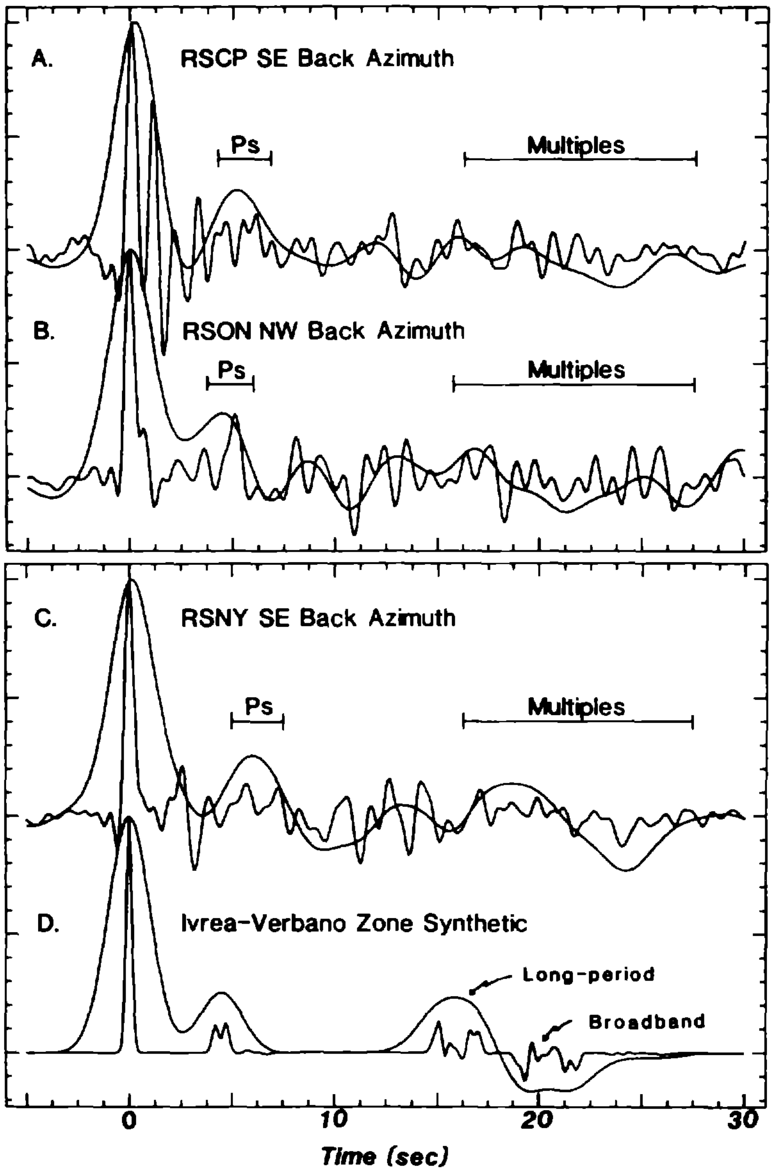
Fig. 1. Physiographic map of North America showing the RSTN.

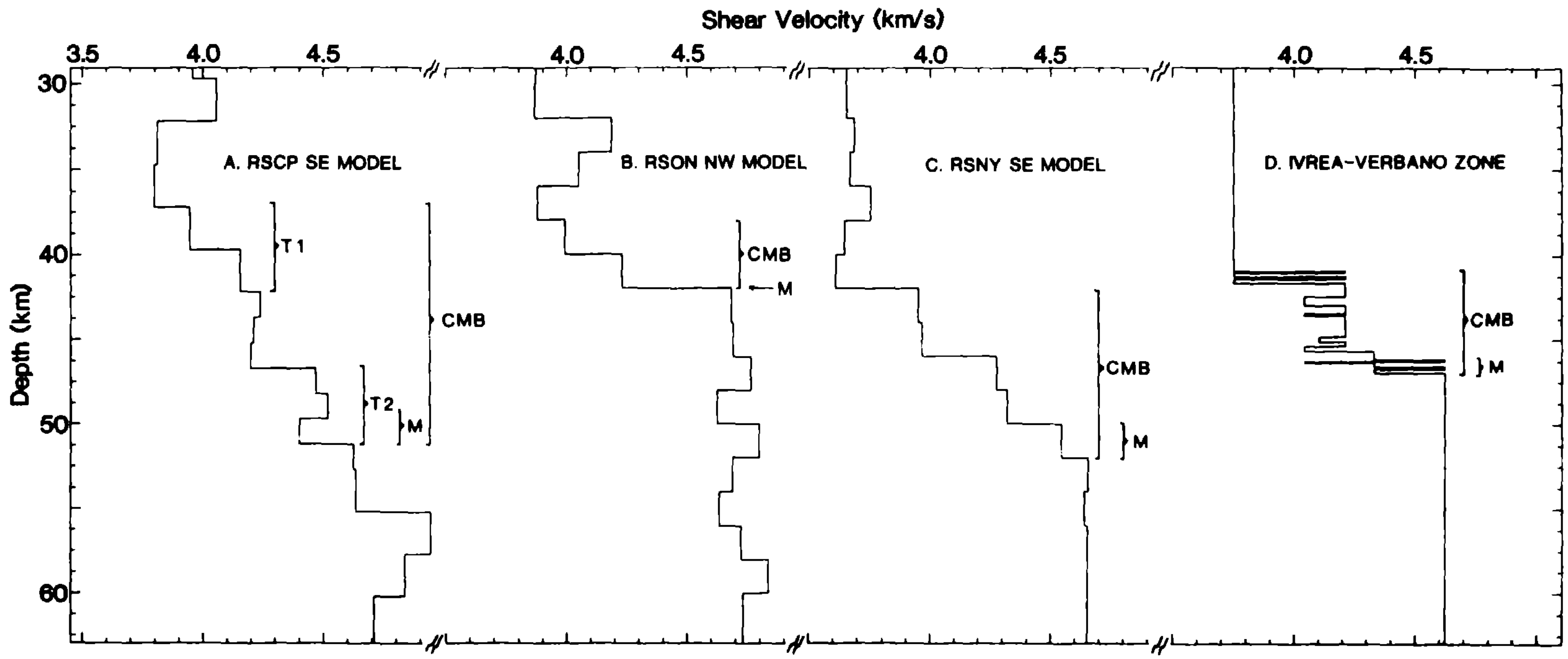
Fig. 2. Radial receiver functions for the 3 RSTN stations and the Ivrea-Verbano zone model. Broadband and longer-period traces are shown for each site. All amplitudes are normalized relative to the direct P-wave amplitude (at time=0). Arrival times for phases from the models shown in Figure 3 are shown above the RSTN data.

Fig. 3. Shear velocity models for only the CMB region. Cases a-c were obtained by inverting the receiver functions shown in Figures 2a-c, respectively. Case d is from laboratory velocity measurements by Fountain (1976). Velocity axis is repeated for each model. Labels are discussed in text.



NORTH AMERICAN
CORDILLERAN
RSNT
CANADIAN
SHIELD
INTERIOR
RSON
RSSD
PLAINS
RSNY
APPALACHIAN
HIGHLANDS
RSCP
ATLANTIC PLAIN


A.
RSCP SE Back Azimuth
Ps
Multiples
B.
RSON NW Back Azimuth
Ps
Multiples
C.
RSNY SE Back Azimuth
Ps
Multiples
D.
Ivrea-Verbano Zone Synthetic
Long-period
Broadband
0
10
20
30
Time (sec)



Shear Velocity (km/s)
3.5
4.0
4.5
Depth (km)
30
40
50
60
A. RSCP SE MODEL
T1
T2
M
CMB
B. RSON NW MODEL
CMB
M
C. RSNY SE MODEL
CMB
M
D. IVREA-VERBANO ZONE
CMB
M